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Decadal Changes in the Edible Supply of Seafood and Methylmercury Exposure in the United States

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Background: Methylmercury (MeHg) exposure is associated with adverse effects on neurodevelopment and cardiovascular health. Previous work indicates most MeHg is from marine fish sold in the commercial market, but does not fully resolve supply regions globally. This information is critical for linking changes in environmental MeHg levels to human exposure in the U.S. population.

Objectives: We used available data to estimate the geographic origins of seafood consumed in the United States (major ocean basins, coastal fisheries, aquaculture, freshwater) and how shifts in edible supply affected MeHg exposures between 2000–2002 and 2010–2012.

Methods: Source regions for edible seafood and MeHg exposure in the United States were characterized from national and international landing, export and import data from the Food and Agricultural Organization of the United Nations and the U.S. National Marine Fisheries Service.

Results: Our analysis suggests 37% of U.S. population-wide MeHg exposure is from mainly domestic coastal systems and 45% from open ocean ecosystems. We estimate that the Pacific Ocean alone supplies more than half of total MeHg exposure. Aquaculture and freshwater fisheries together account for an estimated 18% of total MeHg intake. Shifts in seafood types and supply regions between 2000–2002 and 2010–2012 reflect changes in consumer preferences (e.g., away from canned light meat tuna), global ecosystem shifts (e.g., northern migration of cod stocks), and increasing supply from aquaculture (e.g., shrimp and salmon).

Conclusion: Our findings indicate global actions that reduce anthropogenic Hg emissions will be beneficial for U.S. seafood consumers because open ocean ecosystems supply a large fraction of their MeHg exposure. However, our estimates suggest that domestic actions can provide the greatest benefit for coastal seafood consumers. https://doi.org/10.1289/EHP2644

Introduction

The organic form of mercury, methylmercury (MeHg), is a well-known environmental toxicant that has been associated with long-term neurocognitive deficits in children and impaired cardiovascular health in adults (Debes et al. 2016; Roman et al. 2011). Societal costs of IQ deficits attributed to MeHg exposures are $16 billion in the United States and European Union (EU) alone (Bellanger et al. 2013; Grandjean et al. 2012). In the United States, human MeHg exposure is almost exclusively from seafood consumption (NRC 2000). Between 2000 and 2002, most U.S. population-wide MeHg intake was from fish and shellfish harvested from marine regions, and approximately two-thirds of the U.S. edible seafood supply was imported from other countries globally (Sunderland 2007). A global treaty (the Minamata Convention) was established in 2013 to reduce anthropogenic mercury emissions and associated human and ecological MeHg exposures (UNEP 2013) and entered into force in 2017. Understanding the geographic origins of seafood is essential for linking mercury emissions reductions achieved through this global treaty to changes in human exposures. Here, we quantify changes in the contribution of different seafood categories and marine regions globally to the edible supply of U.S. seafood and associated MeHg exposures between 2000 and 2010.

Human activities have released large quantities of inorganic mercury (all-time total 1,540 Gg) from sources such as mining and fuel combustion (Streets et al. 2017). In 2010, anthropogenic mercury releases to air, land, and water were more than 9,000 Mg compared with natural emissions of 76 ± 30 tonnes/y (Amos et al. 2015; Streets et al. 2017). Inorganic mercury releases can be globally distributed through the atmosphere and major ocean currents, and some is converted by microbes to MeHg in aquatic ecosystems (Cossa et al. 2009; Horowitz et al. 2017; Sunderland et al. 2009). MeHg is the only form of mercury to biomagnify in food webs, reaching concentrations in predatory species such as shark, tuna, and swordfish that are at least a million times higher than seawater (Lavoie et al. 2013). Marine regions are impacted to varying degrees by anthropogenic mercury inputs (Sunderland and Mason 2007). An understanding of seafood supply regions is therefore essential for anticipating impacts of mercury emissions reductions on human exposures.

MeHg concentrations vary by approximately two to three orders of magnitude across seafood categories (Mahaffey et al. 2011). Slower-growing, older fish tend to accumulate MeHg over their lifespan, whereas rapidly growing young-of-the-year fish and low trophic levels species such as sardines, anchovies, and herring have relatively low body burdens (Harris and Bodaly 1998; Karimi et al. 2012; Trudel and Rasmussen 2006). Supply of fisheries products in the United States can be affected by a combination of factors including overfishing, climate driven alterations of marine ecosystems, and global trade (Cheung et al. 2010; Stock et al. 2011; 2017). Overfishing, for example, is known to result in reduced catches and species composition (Pauly et al. 2002; Cheung et al. 2007). Fish consumption preferences of individuals (species and magnitudes consumed) have a strong influence on exposures to MeHg and reflect income, fish price, culture, and globalization of seafood trade (Dey et al. 2005; Fabinyi 2012; Oken et al. 2012).

The main objective of this study is to better characterize the geographic origins of MeHg in seafood consumed by U.S. individuals and temporal shifts in harvesting regions and consumption

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preferences. This is important because different marine regions are affected by atmospheric and riverine mercury inputs of varying magnitudes (Amos et al. 2014; Sunderland et al. 2009); our prior work suggested that the geographic origins of fish influence MeHg exposures of the U.S. population (Sunderland 2007). Here we build on a previously conducted MeHg exposure assessment for the years 2000–2002 by synthesizing fisheries harvest data for the years 2010–2012 from the National Marine Fisheries Service (NMFS) and the Food and Agricultural Organization of the United Nations (FAO). We discuss implications for regulatory strategies aimed at reducing MeHg exposures of U.S. individuals and assess factors driving shifts in U.S. seafood consumption.

Methods

Edible Supply of Seafood

We calculated the edible supply of U.S. seafood from domestic fisheries landings, imports, and exports of seafood reported by the NMFS for the years 2010–2012 (NMFS 2011, 2012, 2013). Data were averaged over a 3-y period to eliminate harvesting anomalies for any individual year. Methods used to calculate edible supply were the same as described in Sunderland (2007) for the years 2000–2002, but MeHg exposure estimates are based on updated total Hg concentrations in fish from the synthesis by Karimi et al. (2012) (see Table S1). Briefly, we first removed all fisheries products not intended for direct consumption by humans. We converted live-weight domestic landings on an individual species basis to edible weights using conversion factors from the literature (see Table S2).

For each market category of seafood, total edible supply was determined by summing domestic edible harvests and imports and subtracting exports and reexports. We estimated the market share (percent) of domestic freshwater species landings from previous work (Carrington et al. 2004) and then scaled the total supply of each fisheries product to match per capita consumption reported by NMFS for each respective year considered. The magnitude of imported seafood harvested from freshwater ecosystems in other countries was estimated using FAO data, as described below.

Geographic Sources of Marine Fish

Domestic landings based on NMFS data were divided into the original categories considered by Sunderland (2007). These categories included domestic landings from the North Pacific and North Atlantic Oceans within the 322-km (200 mi) domestic water limit, and those from beyond the 322-km (200 mi) (high seas) or imported from other countries. We grouped high seas landings with the imported seafood from other countries to further classify the origin of all species caught outside of U.S. domestic waters. We used statistical data from the FAO on global capture production and global aquaculture production to attribute the geographic origins of imported and high seas catches by species (FAO 2014, 2015). For each seafood category, we queried the FAO database for landings from global marine regions (North Pacific, North Atlantic, Equatorial and South Pacific, South and Central Atlantic, Mediterranean Sea, Indian Ocean), aquaculture, and inland waters. Inland waters are defined by FAO as "… lakes, rivers, brooks, streams, ponds, inland canals, dams, and other land-locked (usually freshwater) waters" (FAO 2017). Commercial catches from the Arctic were negligible in most years for almost all species and are therefore not reported in our summary.

For each species, we further classified their habitats (freshwater, aquaculture, coastal, and open ocean) based on a description of their foraging territory from FishBase (Froese and Pauly 2017) and other peer-reviewed literature (see Table S1). Coastal harvests include those from brackish estuarine regions, intertidal areas, and the continental shelf.

Methylmercury Intake Estimates

We estimated contributions to MeHg intake from different harvesting regions globally based on the geographic supply regions for each seafood category contributing to population-wide MeHg exposure. Because 95% of the total mercury burden in predatory fish is MeHg (Bloom 1992), we used total Hg as a proxy for fish MeHg concentration. Shellfish tend to have much lower MeHg fractions, and we thus estimate MeHg content directly for these species (see Table S1). To calculate MeHg exposures in the U.S. population from all seafood products, we used the synthesis of published total mercury measurements by Karimi et al. (2012) unless otherwise noted (see Table S1). Grand mean total mercury concentrations from Karimi et al. (2012) for each seafood category were multiplied by the corresponding edible supply and summed across all seafood categories to calculate total population-wide MeHg intake for each year. Per capita intake was estimated by dividing by the corresponding U.S. population for each year. We hold MeHg concentrations constant between 2000–2002 and 2010–2012 because insufficient data are available to characterize temporal changes in all species over this period. Our temporal analysis of changes in MeHg intake thus reflects decadal changes in seafood consumption preferences at the population level rather than shifting environmental MeHg burdens.

Results

Seafood Harvesting Regions

Our calculations suggest estuarine and marine seafood accounted for 82% of U.S. population-wide MeHg intake between 2010 and 2012. Coastal regions supplied 37% of the MeHg intake and open ocean regions accounted for an estimated 45% (Figure 1). Pelagic-oceanic predators such as swordfish, tunas, and sharks have relatively higher MeHg concentrations than most coastal fish (see Table S1). Thus, estimated MeHg intake was highest from open ocean regions even though the edible supply from coastal regions (49% of the total) was larger than open ocean regions (29%). Farmed fish (aquaculture) and freshwater seafood (inland fisheries) each accounted for 9% of total MeHg intake between 2010 and 2012. Aquaculture species comprised a larger fraction of the total U.S. edible seafood supply (18%) compared with MeHg intake because the most frequently consumed farmed species such as shrimp and salmon have among the lowest MeHg levels (see Table S1).

We estimate that seafood harvested from the Pacific Ocean accounted for more than half of the U.S. population-wide MeHg intake (Figure 1). The North Pacific basin supplied approximately 31% of overall MeHg intake, and an additional 25% is estimated to originate from the Equatorial and South Pacific Ocean. For the North Pacific, most of the MeHg intake (approximately two-thirds) was from coastal fisheries in U.S. domestic waters. By contrast, pelagic (open ocean) species supplied the majority of MeHg intake from the Equatorial and South Pacific Ocean. The North Atlantic accounted for 12% of U.S. population-wide MeHg intake, supplied mainly by coastal fisheries (Figure 1). Domestic landings made up more than 60% of the MeHg intake from coastal fisheries in the North Atlantic in 2010–2012. The Central and South Atlantic Ocean (5%) and Indian Ocean (8%) are estimated to be relatively smaller supply regions for MeHg intake, mainly from open ocean fisheries (e.g., tunas).

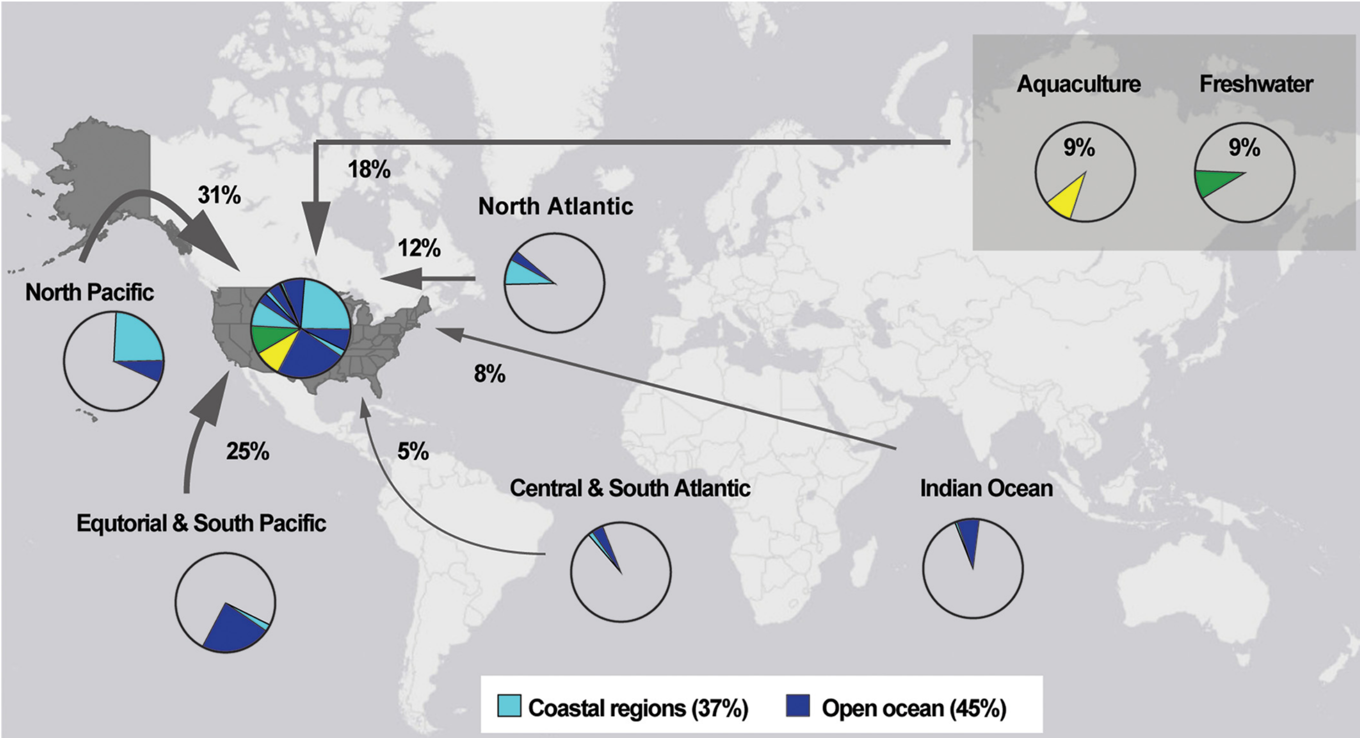

Figure 1. Global sources of U.S. methylmercury exposure from seafood for the years 2010–2012.

Seafood Categories Contributing to Exposure

Shrimp and tuna (canned and fresh) were the dominant seafood categories contributing to the edible supply of seafood in the United States and associated MeHg intake (Figure 2). Shrimp were the most highly consumed seafood in the United States between 2010 and 2012, overtaking fresh and canned tuna, which was highest a decade earlier (Figure 2). When combined, shrimp and tuna accounted for almost 4 of every 10 meals consumed by U.S. individuals between 2010 and 2012. This is consistent with recent data from a national survey of high-frequency fish consumers showing shrimp are the most abundantly consumed seafood item (von Stackelberg et al. 2017). Tuna were a much larger

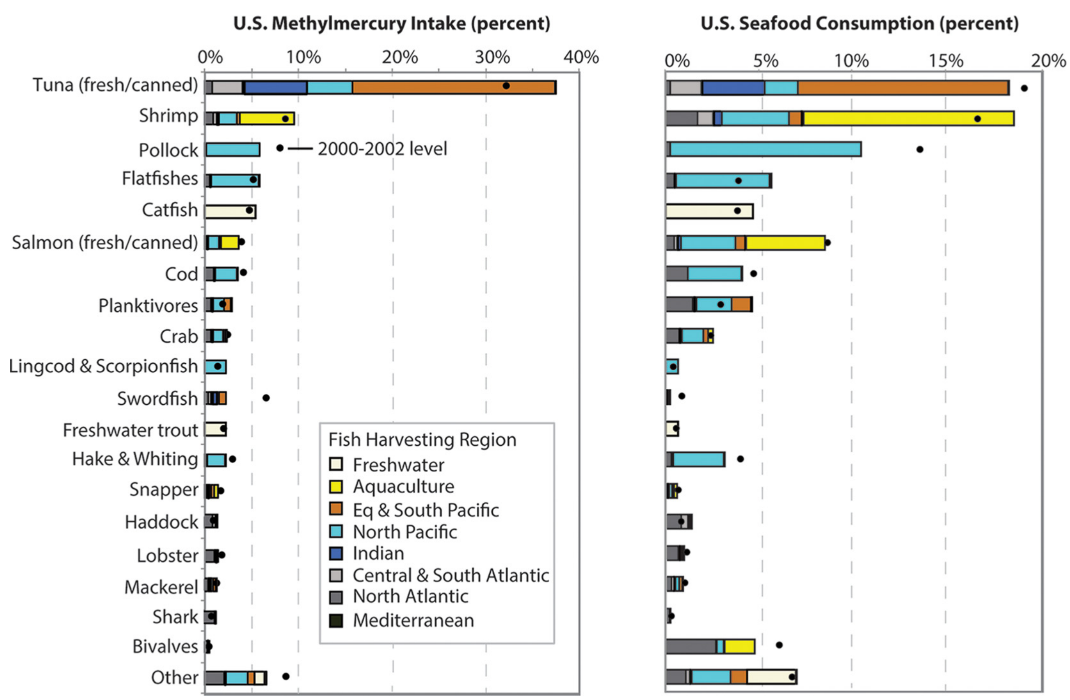

Figure 2. Contributions to U.S. population-wide methylmercury intake from different seafood types and associated seafood consumption for the years 2010–2012. Black circles show 2000–2002 values. Flatfishes includes sole, flounder, and halibut. Planktivores includes herring, sardine, and anchovies. Bivalves includes mussels, clams, oysters, and scallops. Shrimp includes all preparation types (canned and fresh). Data used to generate this figure are provided in Tables S2 and S3.

MeHg intake source (38%) than shrimp (approximately 10%) due to relatively higher MeHg concentrations (see Table S2). Harvesting regions also differ, with most tuna from the Equatorial and South Pacific and Indian Oceans, whereas shrimp were predominantly from aquaculture and the North Pacific (Figure 2). The FAO reported a small fraction of the fresh and frozen tuna (~0.1%) comes from aquaculture production, presumably from captured juveniles raised to adult size, but this was negligible compared with capture fisheries (FAO 2014, 2015).

Pollock, flatfishes (sole, flounder, and halibut), and freshwater catfish each also contributed more than 5% of population-wide MeHg exposure between 2010 and 2012. Salmon (fresh and canned) made up a substantial portion of the U.S. edible seafood supply (8.7%) but have low MeHg concentrations and accounted for only 4% of population-wide MeHg intake. Pollock and flatfishes were predominantly harvested from the North Pacific Ocean. Catfish were the most abundantly consumed freshwater fish species on a population-wide level.

Decadal Changes in Seafood Consumption

U.S. edible seafood supply remained relatively constant between 2000–2002 (1,960 thousand tonnes) and 2010–2012 (2,130 thousand tonnes). When adjusted for population growth, per capita seafood consumption declined from 18.9 g per person per day in 2000–2002 to 18.7 g per person per day in 2010–2012 (see Table S2). Shifts in MeHg exposure reflect changes in the seafood consumption patterns shown in Figure 2 because levels of MeHg in seafood are held constant in our analysis.

Among seafood categories, shifts in tuna consumption have a large impact on MeHg exposure (Table 1). Overall consumption of tuna in 2010–2012 declined slightly relative to a decade earlier (Figure 2; see also Table S2), but estimated MeHg exposure from this category increased due to greater consumption of fresh and frozen tuna. Fresh and frozen tuna contain fillets of larger, older fish such as bigeye and albacore that are generally higher in MeHg than the skipjack and yellowfin tuna species found in canned light meat products (see Table S1). Fresh and frozen tuna increased from 10% to 29% of the edible tuna supply between 2000–2002 and 2010–2012 (Table 1). Meanwhile, canned light meat tuna declined from 76% of total edible tuna supply to 56% over this same period. Notable changes in consumption of other species are also apparent in Figure 2. Consumption of shrimp increased, while pollock, cod, and swordfish all declined. Overall, per capita MeHg exposures were similar over these two time periods, but species consumed by U.S. individuals were harvested from different environments globally, as discussed further below. This is critical for anticipating future trends in population-level MeHg exposures because environmental mercury burdens change over time and vary geographically (Amos et al. 2013).

Discussion

Drivers of changes in U.S. Seafood Supply

Changes in the edible supply of U.S. seafood reflect the combined influences of consumer preferences, global trade of fisheries products, and shifts in environmental conditions that alter locations and types of fish harvested. Shifts in consumer preferences away from canned light meat tuna (skipjack and yellowfin tuna) began in the 1990s concurrently with advertising campaigns linking dolphin capture to yellowfin tuna fisheries (FAO 2004). The uptick in shrimp consumption over the past two decades may reflect its substitution by some consumers who previously chose canned light meat tuna (Figure 2). Such substitution would lead to lower overall MeHg exposures in those individuals. The large growth in sashimi lunch meals (including bigeye and albacore tuna) across the United States over the last two decades is reflected in the large increase in edible supply of fresh and frozen tuna between 2000–2002 and 2010–2012 and a slight increase in total per capita MeHg exposure by 0.04 μg per person per day.

We infer from our analysis of edible seafood supply between 2000–2002 and 2010–2012 (Figure 2; see also Table S2) that oceanic conditions affected the edible seafood available in the U.S. commercial market (Figure 3). Aquaculture production supplies large quantities of salmon, shrimp, and bivalves (mussels, clams, oysters, and scallops) to the U.S. commercial market. Between 2000–2002 and 2010–2012, capture fisheries in the North Pacific declined for both salmon and shrimp, while aquaculture production grew across all three seafood categories (Figure 3A). Increases in shrimp consumption in the U.S. population were thus largely supplied by growth in farmed seafood products rather than wild harvests (Figure 2).

Sardine and anchovy fisheries fluctuated in abundance with high anchovy production between 2000 and 2002 and high sardine production between 2010 and 2012 (Figure 3). This pattern has been observed since the 1950s and follows the multidecadal oscillation in temperature and circulation in the Pacific Ocean, with warm seawater temperatures favoring sardine production and cool seawater temperatures favoring anchovy fisheries (Chavez et al. 2003). This example illustrates how fisheries consumed in the U.S. are sensitive to interannual variability in global climate.

Cod fisheries are also known to be sensitive to changes in seawater temperature (Pershing et al. 2015; Planque and Frédou 1999). Our analysis of fisheries supply regions suggests harvesting regions supplying cod to the U.S. commercial market shifted to higher latitudes between 2000–2002 and 2010–2012 (Figure 3B). Increases in edible supply are apparent in the North Atlantic and North Pacific compared with declines in the Equatorial and South Pacific and Atlantic and Indian Oceans. Total supply from the North Atlantic Ocean increased by 140% in 2010–2012, contrasting with a 47% decline in yields from domestic vessels relative to 2000–2002. This can be explained by unprecedented increases in seawater temperature in the Gulf of Maine since

Table 1. Decadal changes in U.S. edible supply and population-wide methylmercury exposures from tuna.

Type of tuna	2000–2002	2010–2012	Change in edible supply (%)
Canned white tuna			
Edible supply in tonnes (% of edible tuna)	52,500 (14)	60,900 (15)	+5
Percent of U.S. MeHg exposure (%)	18	9	
Canned light meat tuna			
Edible supply in tonnes (% of edible tuna)	289,000 (76)	223,000 (56)	−39
Percent of U.S. MeHg exposure (%)	9	12	
Fresh and frozen tuna			
Edible supply in tonnes (% of edible tuna)	38,800 (10)	115,400 (29)	+14
Percent of U.S. MeHg exposure (%)	6	17	

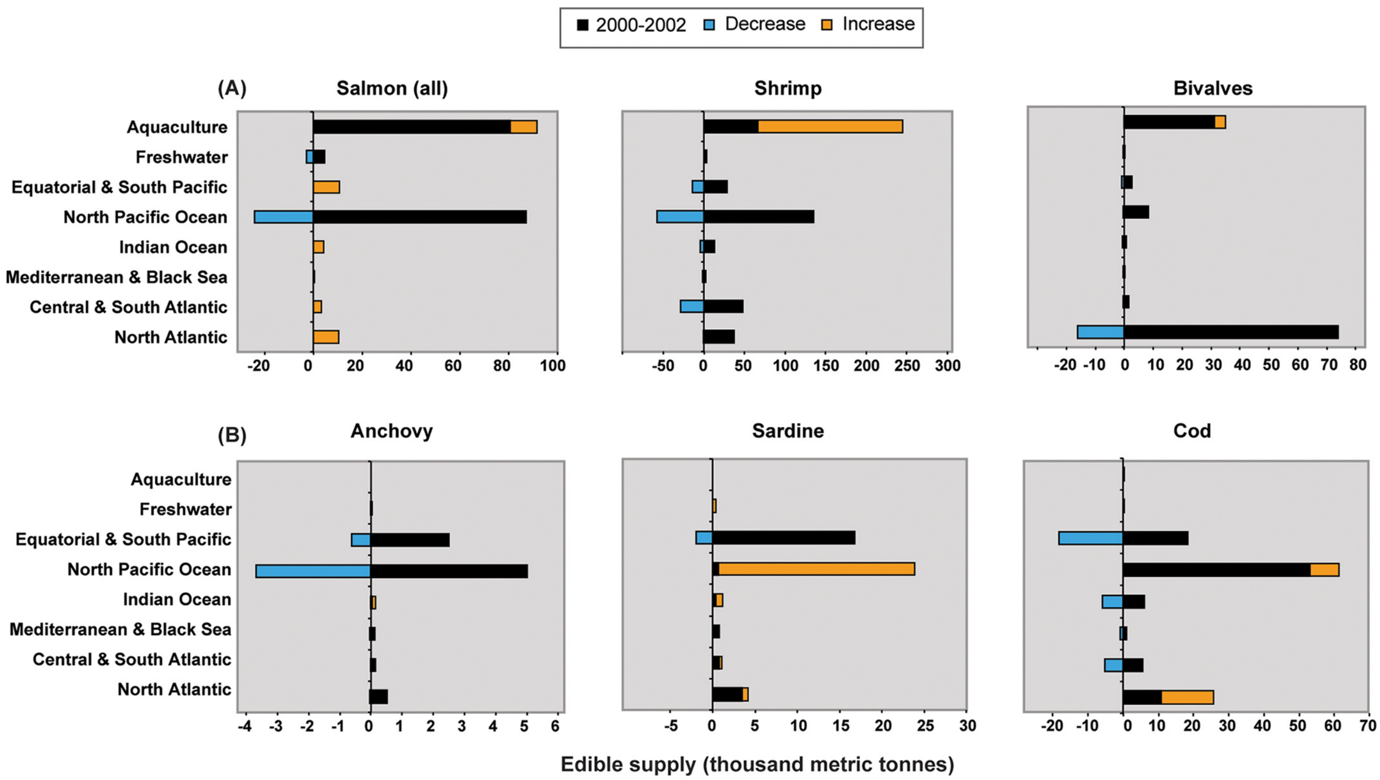

Figure 3. Changes in U.S. edible supply of seafood between 2000–2002 and 2010–2012. (*A*) Changes in supply of species predominantly from aquaculture. (*B*) Fisheries known to be affected by climate variability.

2004, which is a major domestic harvesting region for North Atlantic cod (Pershing et al. 2015). Such changes have lowered productivity in U.S. domestic waters but may have had a positive effect on capture fisheries at higher latitudes in Greenland, the Barents Sea, and Iceland (Fogarty et al. 2008; Pershing et al. 2015; Planque and Frédou 1999). Seawater temperature increases are thought to have driven large-scale migration of cod stocks toward the poles, leading to historic increases in biomass in Barents Sea fisheries (Kjesbu et al. 2014). Shifts in the sources of edible supply of cod in the U.S. commercial market thus reflects a direct impact of warming ocean conditions on the diet of American individuals.

Implications for Future MeHg Exposures

Understanding the geographic sources of MeHg exposure from fisheries is essential for prioritizing strategies to reduce environmental MeHg concentrations and anticipating future risks. MeHg concentrations in fish reflect environmental quality in the ecosystems from which they are harvested, linking human exposures to global environmental quality. Coastal ecosystems account for 37% of U.S. population-wide MeHg intake and can be expected to respond to domestic efforts to curb mercury pollution. For example, domestic reductions in emissions from U.S. coal-fired power plants have been linked to declining MeHg concentrations in bluefish from the Gulf of Mexico (Cross et al. 2015; Sunderland et al. 2016).

This work confirms that the largest fraction of U.S. MeHg exposure is from open ocean fisheries (45%). We estimate that the largest fraction of open ocean MeHg is derived from the Equatorial and South Pacific Ocean because of the importance of this region for global tuna fisheries (Figures 1 and 2). Primary releases of anthropogenic mercury have shifted over time from North America and Europe to Southeast Asia and India (Streets et al. 2017). Recent modeling efforts show that 80% of global atmospheric mercury is deposited to the global oceans annually, with 49% in tropical ocean regions (Horowitz et al. 2017). Signing of the Minamata Convention in 2013, and its entry into force in 2017, mark the beginning of global efforts to reduce anthropogenic mercury burdens in the environment (Selin 2014). This agreement is thus essential for reducing exposures of U.S. individuals, as well as other populations globally that rely on fisheries.

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